THE OPACITY OF SPIRAL GALAXY DISKS

Dust opacity from calibrated counts of distant galaxies.

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Abstract The opacity of foreground spiral disks can be probed from the number of distant galaxies seen through them. To calibrate this number for effects other than the dust extinction, Gonzalez et al (1998) developed the "Synthetic Field Method". A synthetic field is an extincted Hubble Deep Field added to the science field. The relation between the dimming and the number of retrieved synthetic galaxies calibrates the number found in the science field. Here I present results from counts in 32 HST/WFPC2 fields. The relation between opacity and radius, arm and disk, surface brightness and HI are presented. The opacity is found to be caused by a clumpy distribution of clouds in the disk. The brighter parts of the disk -the center and arms- are also the more opaque ones. The dust distribution in spiral disks is found to be more extended than the stellar disk. A comparison between HI column densities and opacity shows little relation between the two.

Keywords: dust, spiral disks, spiral galaxies, absorption, extinction, interstellar matter

1. Introduction

The measure and extent of the dust absorption by spiral disks has been the subject of study and even controversy for some time. New models of the disk's energy household (e.g. Dopita, 2005) and a wealth of observational data (e.g. Regan, 2005 and Kennicutt, 2005), promise a better understanding of the role of dust in the disks. Still, there are several questions regarding the distribution of dust clouds in the spiral disk which should be addressed: to which radius does dust extend and is dust spatially correlated to the stellar distribution or the atomic hydrogen gas?

One possible technique to answer these questions is to use the number of distant galaxies seen through a foreground disk as an indicator of disk opacity.

2. What is the "Synthetic Field Method"?

For a useful measurement, one needs to calibrate the number of distant galaxies seen through a foreground for effects other than the extinction by dust. The calibration is done with the "Synthetic Field Method" (Figure 1). The distant galaxies in the science field are counted (step 1). An average background field is added to the science field to create a "synthetic field". The average background field is artificially dimmed in progressive "synthetic fields" (step 2). The numbers of retrieved synthetic galaxies for each value of the dimming is found (step 3). The relation $A = \quad - 2.5 \; Log_{10}(N/N_0)$ is fitted to the relation between the numbers of galaxies (N) and the dimming (A) of the synthetic fields (step 4). The free parameters are the slope (C) and the number of galaxies without any dimming (N_0). The intersection between the fit and the number of actual distant galaxies found in the science field gives the average opacity of the science field (step 5)[1]. This comparison between counts can be done for individual fields but also for multiple fields, combined based on disk characteristics: radius, arm or disk region, surface brightness or HI column density. [2]

3. The opacity profile of spiral disks

Figure 2 shows the stacked radial opacity profile of our entire sample of 32 HST/WFPC2 fields. From Figure 2, we can conclude that the average radial opacity profile of spiral galaxies remains relatively flat for most of the disk and only tapers off somewhere beyond the R_{25}. This was already suspected from sub-mm observations (e.g. Nelson et al., 1998 and Zaritsky, 2005). This profile has not been corrected for inclination effects, as this depends greatly on the assumed dust geometry.

The average color of the galaxies in the science fields does not change however (Figure 2, top panel). If the diminishing effect of the dust in the ISM would have been due to a uniform screen, the average color would have changed with the total amount of attenuation according to an Extinction Law. However, if the dust in the disk is relatively patchy, the attenuation is derived from the number of absent galaxies while the color is from those that have been detected relatively unhindered by dust in the disk. The average disk opacity in Figure 2 can therefore be interpreted as a cloud covering factor.

Separate profiles for the arm and disk sections of the foreground galaxy can also be made (Figure 3). These opacity profiles show a strong radial relation in the arms and a much flatter profile in the rest of the disk. When these profiles are compared to the opacity values from occulted galaxy pairs (White

et al., 2000; Domingue et al., 2000), there is a remarkably good agreement between these completely different methods. White et al., 2000 also found a gray behaviour but Keel and White, 2001 found that the Galactic Extinction law re-emerged for measurements below a linear scale in the disk smaller than 100 pc.

4. Dust, gas and stars

The strong radial relation for the spiral arms hints at a direct relation between the amount of dust in the disk and the surface brightness of the disk. A similar relation between overall disk opacity and brightness was found by Tully et al., 1998; Masters et al., 2003. However the much flatter distribution of the opacity in the rest of the disk does suggest that the dust may be more distributed like the atomic hydrogen.

To find the relation between opacity and surface brightness, each distant galaxy, from both synthetic and science fields, are flagged with the surface brightness in 2MASS images. The numbers of galaxies as a function of near-infrared surface brightness are shown in Figure 4 for all of the disk and the arm and non-arm regions separate. As could be expected from Figure 3, there is a strong relation between surface brightness and opacity in the arm regions but none in the non-arm part of the disk.

The relation between atomic hydrogen and dust might reveal more on the hidden constituents of the ISM. Due to limitations of the SFM measurements and lack of HI maps, Figure 5 shows the ratio of the HI column density from radial profiles from the literature and the opacity measured from counts of galaxies in the same radial bin. No direct relation is evident, mainly because opacity profiles rise towards the center of galaxies and HI profiles stay flat or decrease. It is possible that dust correlates with the total gas content in the disk, both the molecular and the atomic.

5. Final Remarks

The counts of distant galaxies have proven themselves to be a good indicator of disk opacity, provided they are calibrated with the SFM. Improved statistics from many HST fields have lent insight into the distribution of dust in the disk and into the relation with the stellar content and atomic gas. The radial opacity profile extends to well beyond the optical disk and appears caused by patchy dust. The dust clouds correlate with stellar light in the arms but there is additional constant disk component which is more dominant at higher radii.

The radial profile implies that there are dust clouds outside the optical disk. This seems in agreement with the SINGS extinction maps (Regan, 2005) and PAH emission maps from the SINGS project (Kennicutt, 2005) but an exact comparison remains to be made. However, we know that starformation and

HII regions can be found at hitherto unprecedented radii. The presence of dust is therefore not unreasonable. The question remains how much there is.

One implication of the relation between opacity and surface brightness in the arms is that a light-profile derived from the non-arm regions can be a maximum disk or a scaling of that but that a profile that includes the arm regions will be less concentrated than the actual distribution of mass. This may be another contributor to a slightly different normalization of the Bell and de Jong, 2001 color-M/L relation (de Jong, 2005).

The profiles of opacity and HI column density are not correlated. Since the opacity keeps rising in the center, it is very possible that the overall disk opacity relates in some way to the total gas content or even just the molecular component.

A similar radial profile and HI-to-dust ratio for spiral disks have also been found in sub-mm observations of disks. This implies that a substantial fraction of the dust responsible for the disk opacity is cold.

Future application of the counts of distant galaxies include probing the edge of the dust disk, constraining the average cloud size, a comparison with sub-mm observations to constrain dust emissivity and a direct comparison with column density

Notes

1. A comprehensive description of the "Synthetic Field Method" and the uncertainties involved is presented in Holwerda et al., 2005a and Holwerda, 2005. The effects of disk's characteristics on the accuracy is discussed in Holwerda et al., 2005e.
2. The numbers of distant galaxies in a single HST/WFPC2 field are only sufficient for a relatively uncertain opacity measurement. To counter this much more solid angle from several HST observations need to be combined.

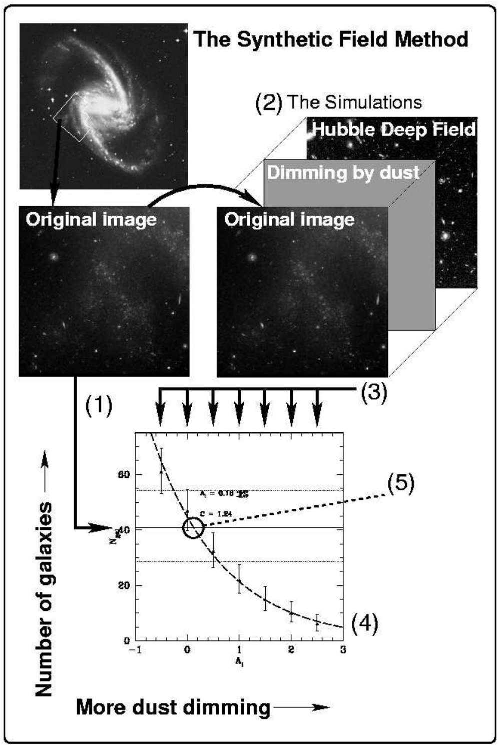

Figure 1 A schematic of the "Synthetic Field Method". First a WFPC2 field is retrieved from the Hubble Space Telescope archive and redrizzled.

The SFM steps are:

1. The number of distant galaxies in the original science field are counted.
2. The "synthetic fields" are made by combining a dimmed Hubble Deep Field with the science field.
3. The numbers of synthetic galaxies are counted in the synthetic fields.
4. $\mathrm{A} = -2.5\ \mathrm{Log}_{10}(\mathrm{N}/\mathrm{N}_0)$ it fitted to the number of synthetic galaxies (N) as a function of the applied dimming (A).
5. From the intersection between the number galaxies in the science field and the fit, the average dimming in the image is found.

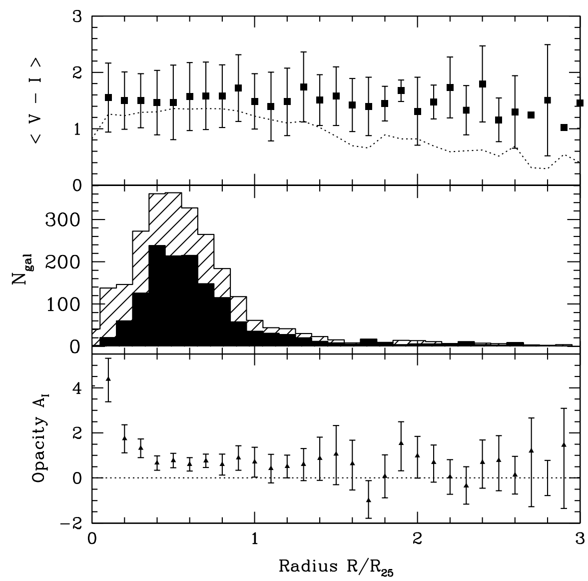

Figure 2 The stacked radial opacity profile for all 32 galaxies in the sample. The counts of galaxies were ordered according to deprojected radial distance from the foreground galaxy's center, expressed in R_{25}. Top: the average color of distant galaxies in the science fields. Middle: the number of distant galaxies in the science field (filled) and the synthetic fields without any dimming (shaded). Bottom: the disk opacity as a function of radius derived from the numbers of distant galaxies. Since most of the WFPC2 fields were pointed at the disk of these galaxies, the opacity measurements are the most accurate there (from Holwerda et al., 2005b).

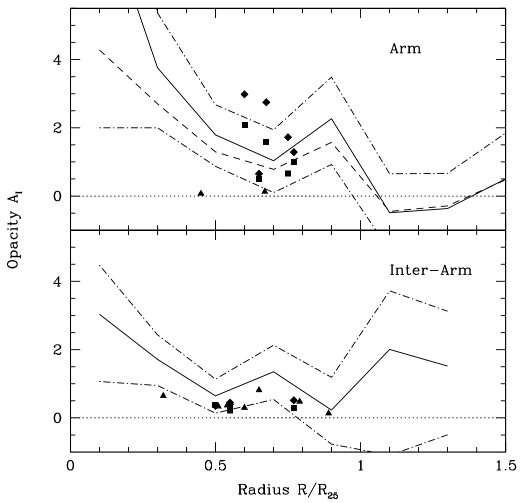

Figure 3 The stacked radial opacity profiles for the arm and inter-arm regions of the disks. The filled squares and triangles are the measurements by White et al., 2000 and Domingue et al., 2000 respectively. The dashed/dotted lines are the uncertainties in the SFM measurements. higher values for spiral arm opacity have been found in earlier photometric studies (e.g. Elmegreen, 1980; **?**; **?**; **?**)

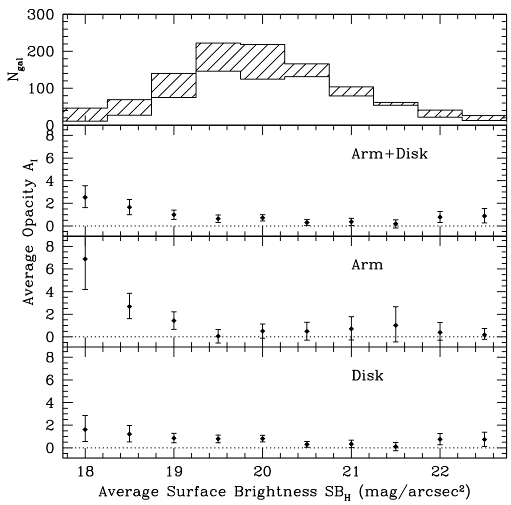

Figure 4 The disk opacity as a function of surface brightness. The distant galaxies - real and synthetic- are sorted by surface brightness in the entire sample. Top: the histograms of distant galaxies (shaded for the synthetic fields and the line for the science field). Top middle: the derived opacity as a function of surface brightness. Bottom two plots: the surface-brightness and opacity plots for the arm (top) and disk (bottom) parts of the spiral galaxy.(from Holwerda et al., 2005d)

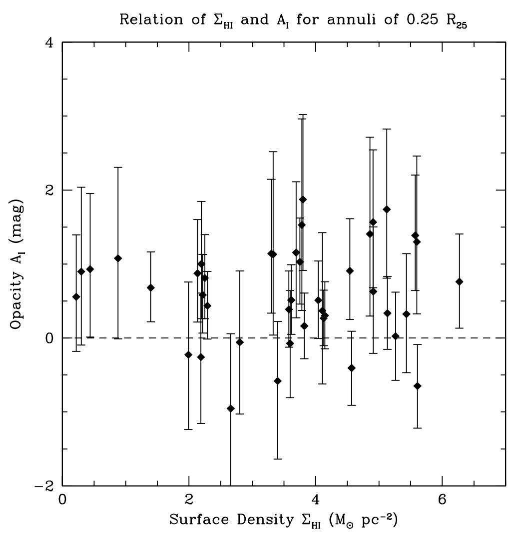

Figure 5 The ratio of HI column density and opacity in radial annuli of 0.25 R_{25}. Opacity measurements in individual galaxies remain uncertain due to cosmic variance in the number of distant galaxies behind each foreground galaxy. An improvement would include compare galaxy number directly as a function of HI column density (e.g. Cuillandre et al., 2001), much like Figure 4. (from Holwerda et al., 2005c)

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